Chapter 7

Applications of Advanced Controls

This chapter gives examples of engineering projects where advanced control methods have been used or studied. The first example is from Brazil where thyristor controlled series compensation (TCSC) is used to damp interarea oscillations. Section 7.2 presents the control analysis of a potential 500-kV TCSC installation in China. Section 7.3 explores how new distributed-measurement technology can be used to improve dynamic and transient system stability. Section 7.4 describes active-load modulation to improve stability. Section 7.5 presents energy source power system stabilizers.

7.1 Brazilian North–South Interconnection—Application of Thyristor Controlled Series Compensation (TCSC) to Damp Interarea Oscillation Mode

This example deals with a pioneer commercial application of TCSC to damp the low frequency interarea oscillation mode in the Brazilian north–south interconnection [7-1]. The north–south interconnection connects Imperatriz substation (in the State of Maranhão) to Serra da Mesa (in the State of Goiás). The interconnection is a single 500-kV line and is 1,020 km long. The line is designed to transmit up to 1,300 MW, with suitable operation required from no load up to maximum flow in both directions. The interconnection was commissioned in early 1999 and reduces the risk of energy deficits. A TCSC control system for transient and dynamic stability improvement was designed and, together with extensive study results, formed the basis for the TCSC locations and equipment specification. Use of two small TCSCs (6% compensation each) proved to be very effective in damping the interarea mode, and eliminated the technical restriction on the AC transmission alternative.

Main aspects. There are two main electric power systems in Brazil which were not previously interconnected: the south/southeast (or south system) and the north/northeast (or north system) systems. They are essentially hydroelectric systems and include more than 95% of the total national production and consumption. The installed generation capacity in South/Southeast and North/Northeast systems is about 48 GW and 14 GW, respectively. See Figure 7-1.

Technical and economical feasibility of the interconnection was studied since 1992. The "North–South Interconnection" will exploit hydrologic diversity between the systems, achieving energetic benefits estimated at about 600 MW-year. Power flows will occur in both directions, depending on the actual hydrologic conditions.

Two transmission alternatives were considered and analyzed to establish the North–South Interconnection: a DC ±400-kV bipole and a single 500-kV AC compact transmission line (4x954 MCM bundle), 1,020 km long. In both cases, the interconnection links the 500-kV substation of Imperatriz (north system) to the Serra da Mesa power plant (south system).

Fig. 7-1. Brazilian North–South Interconnection—geographic location.

From a purely technical viewpoint, this long, low capacity interconnection between two large systems having different planning and operating criteria is a textbook application for HVDC transmission technology. From a strategic and political viewpoint, however, the AC transmission alternative is highly attractive for making inexpensive hydroelectric energy available to a rapidly growing area, and for future generation developments located over a vast geographic area having enormous economic potential. Six hydroelectric plants may be built along the same route in the next two decades, and other 500-kV AC transmission links are planned to cater for this additional generation.

When comparing the technical behavior of the two alternatives, it was verified that the AC solution presented a low frequency (0.18 Hz), poorly damped interarea oscillation mode. This oscillation of wide amplitude (± 300 MW) represented a serious technical restriction for the AC alternative. On the other hand, this alternative presented significant advantage in terms of costs, besides the strategic and political benefits mentioned above.

Traditionally, the problem of electromechanical oscillations in the range of 0.5 to 2.0 Hz has been solved by power system stabilizers (PSS) in the main synchronous generators.

For lower frequency modes (< 0.3 Hz), however, effective damping is a difficult task. The main drawbacks of this solution for the north–south interconnection are listed below [7-1]:

1. Modified PSSs would be needed in all major power plants of the northeast system;
2. The modified PSSs, assumed to be of fixed structure and fixed parameters, would not always ensure adequate damping for the north–south mode for the various scenarios considered in the study;
3. The frequency range of electromechanical oscillations to be damped by the modified PSSs is too wide to yield reliable operation;
4. Electromechanical oscillations within the northeast system (local modes) and between the north/northeast systems (interarea mode) could have their damping reduced by the action of the modified PSSs;
5. Practical limitations on maximum PSS gain at very low frequencies may reduce the damping of these modified stabilizers.

To solve the sustained oscillation problem thyristor controlled series compensation (TCSC) was proposed in the interconnection (transmission line Imperatriz–Serra da Mesa). This solution was much more efficient than PSS in providing damping for all possible system scenarios and contingencies. One great advantage of this solution is the fact that the TCSCs are located in the link that introduces the interarea mode and they are tuned only for this mode, not having any effect on the other modes presented in the system. So if this link is disconnected, the TCSCs together with the interarea mode cease to exist. The stability of the two isolated systems (north and south) in this case is guaranteed by PSSs exactly as before the advent of the interconnection.

The TCSCs at each end of the intertie are modulated using local line power measurements. Figure 7-2 shows simulation results. Commissioning tests verified the powerful damping performance of the TCSCs [7-2].

7.2 Analysis and control of Yimin–Fengtun 500-kV TCSC system

References 7-3–5 present research done for the thyristor controlled series compensation (TCSC) to be situated on the main corridor of the 500-kV transmission system of northeast China. Power will be transferred from Yimin plant in Mongolia, with 2200 MW capacity, to the load centers through a 500-kV parallel transmission line covering a distance of 1300 km. The paper is motivated by the real engineering project and presents on-going research for TCSC models, control algorithms, simulation software and implementation. Because of future development of the transmission system, the controller design must be systematic and robust.

The Yimin–Fengtun TCSC projects has the following distinctive features:

- It’s located on an important corridor of the main grid. The theories and the schemes must be applied to the real engineering project and must be easy to manipulate.
- It’s required to increase dynamic, transient and voltage stability.

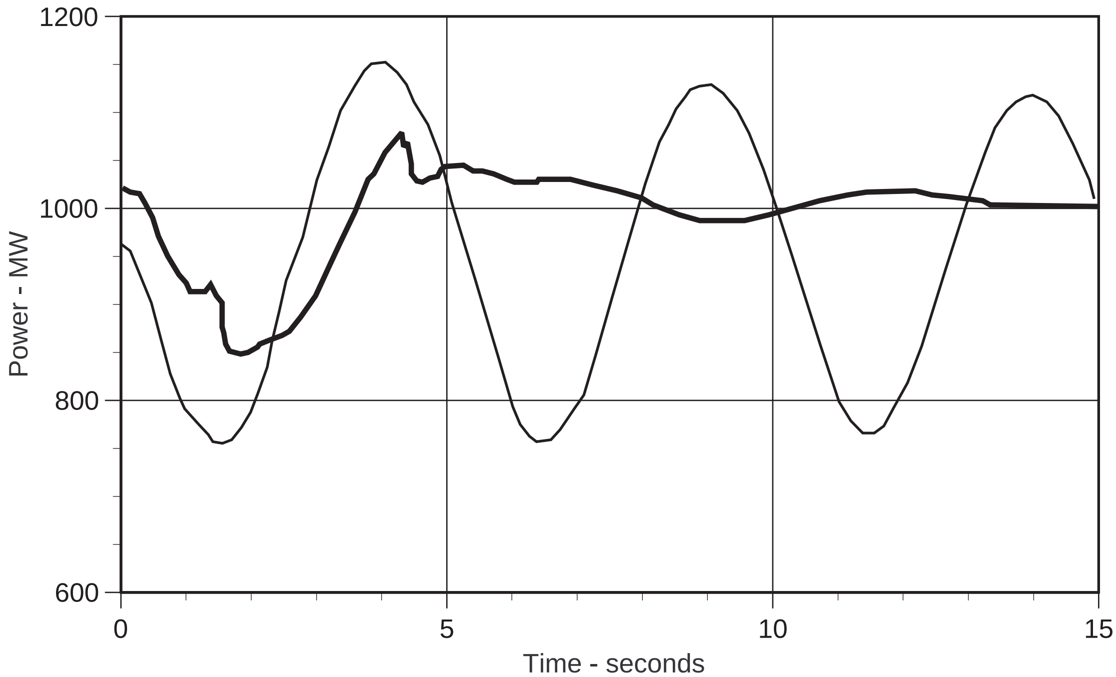

Fig. 7-2. Simulation of fault with line outage in south system [7-1]. Thin line without TCSCs, thick line with TCSCs.

- The controller must be robust. It should adapt to not only the variation of operation conditions, but also future changes of grid topology. It's important to have control schemes that require local signals only and are independent of system models.
- Because of the project's importance, the research should be broad.

Without a TCSC, the system suffers severe transient and dynamic instabilities. The study shows that the TCSC with proper control schemes can schedule power flow flexibly, and improve transient and dynamic stability. The influence of the voltage protection of the metal oxide varistor (MOV) is included in the control model and design. Auto-disturbance rejection control (ADRC), fuzzy control, and nonlinear adaptive scheme are studied. Simulations show the effectiveness of the control schemes. The combined effect of electromagnetic and electromechanical transients has been studied.

7.3 Wide-Area Stability Control

New distributed measurement technology using the global positioning system and accurate phasor measurements units have developed steadily in recent years to become the most powerful source of wide-area dynamic information. Reference 7-6 explores new ways of putting this extended real-time knowledge of the power system behavior into use by means of supplementary feedback loops which improve dynamic and transient system stability and, ultimately, increases the transmission capacity.

The design of such advanced controllers is based on a two-stage methodology. The first step is built on a powerful pulse response-based, numerical sub-space, state-space identification algorithm to identify a reduced-order small-signal MIMO model of the open-loop system. The second step is to select an appropriate control structure, and then tune the stabilizer parameters accordingly. To tackle the most difficult situations, the architecture selected comprises several dynamic feedback loops, each consisting of a high-order differential filter. Controller tuning is then performed by minimizing a selective modal performance index in the parameter space.

Adding stability and robustness constraints greatly improves the engineering significance of the resulting design. For illustration, a three-loop stabilizer was designed for a major synchronous-condenser station in an actual power system that simultaneously uses two global and one local input signals. Both linear and nonlinear simulation results clearly demonstrate the added value of wide-area information when properly included in power system stabilizer design.

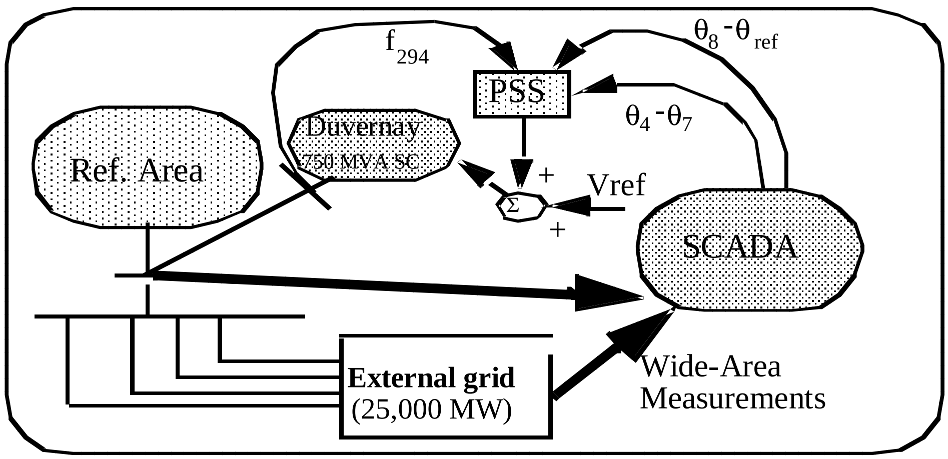

Fig. 7-3. Decentralized/hierarchical PSS located at the Duvernay synchronous condensers (SC).

The architecture of the Hydro Quebec test system used in reference 7-7 is recalled in Figure 7-3 .The target PSS is at the Duvernay synchronous condenser in the reference area. This site was chosen because it shows the highest controllability index over the broadest frequency range. The three inputs of the PSS are the following:

$$y = \lfloor f_{294} \quad \theta_4 - \theta_7 \quad \theta_8 - \theta_{Ref} \rfloor$$

where f_{294} is the local bus frequency at Duvernay, and $\theta_4 - \theta_7$ and $\theta_8 - \theta_{Ref}$ are angle shifts between the subscript areas. Based on three typical contingencies, Figures 7-4 and 7-5 provide some interesting clues as to what added value should be ascribed to the information exchange paths outlined on Fig. 7-3. On the first contingency, the local loop alone was sufficient to stabilize the system. However, it was unable to do the same for the second and third, although its positive action provided 5–10 seconds relief before actual breakdown. Therefore, information exchange really has some monetary value, which in some cases could pay for the implementation costs and cover the additional risks inherent in long-distance telemetry.

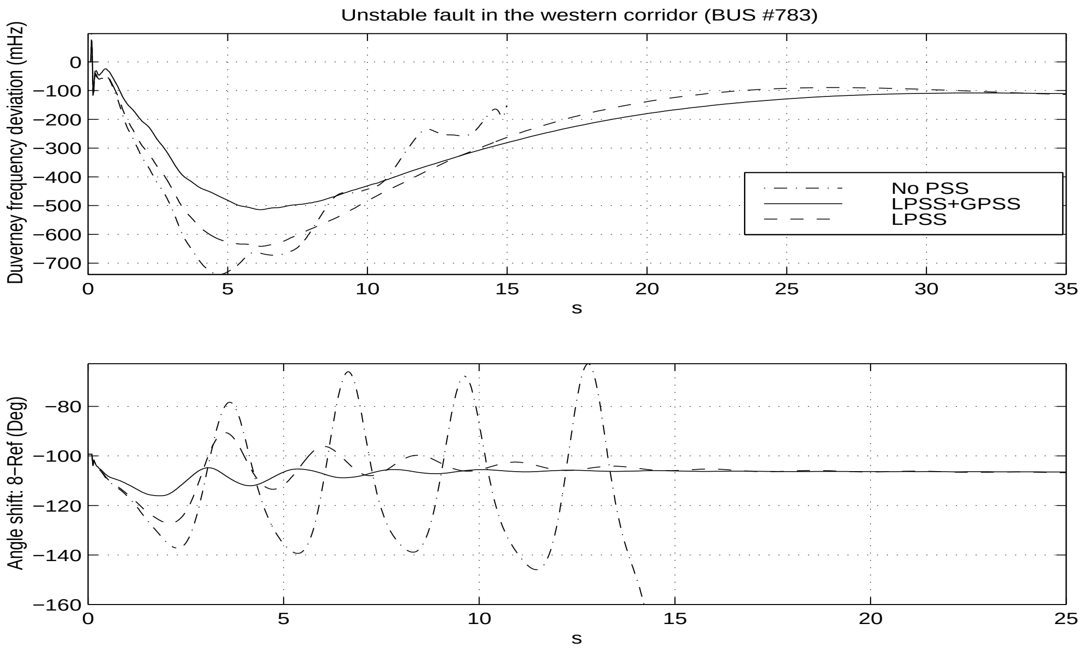

Fig. 7-4. First contingency: The local loop alone prevents the system from collapsing.

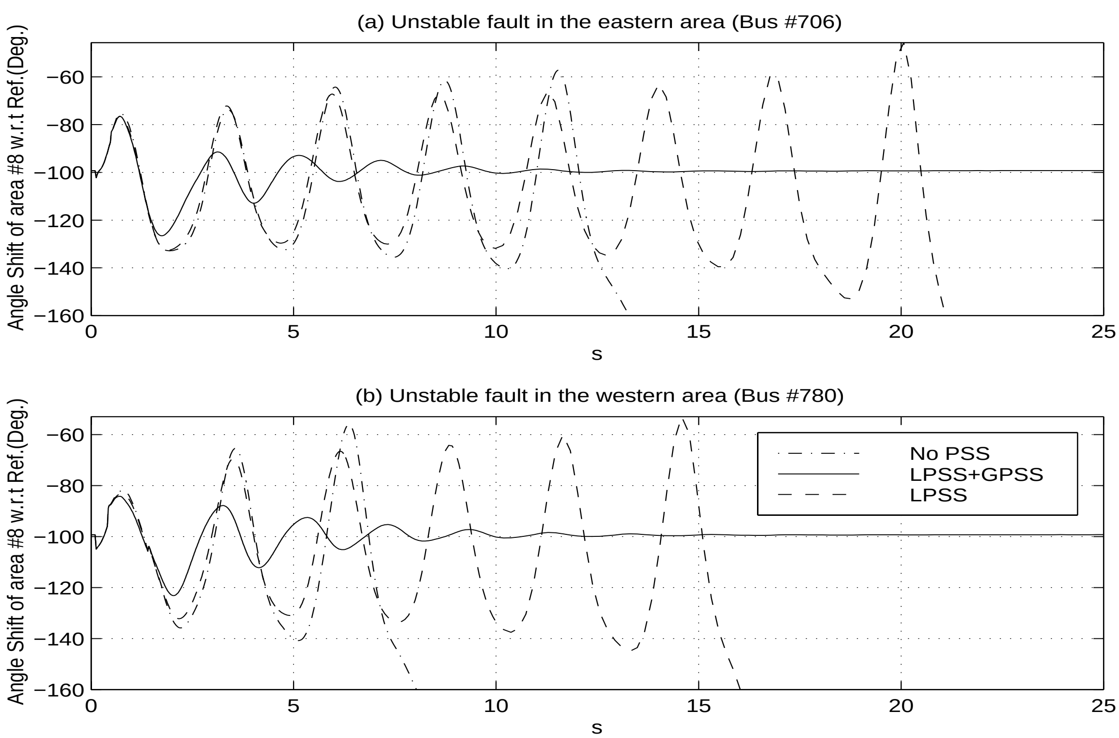

Fig. 7-5. Second and third contingencies: The local loop alone substantially improves the system performance, but doesn't prevent instability.

7.4 Active-Load Modulation for Stability Control

The first subsection describes large-scale load modulation and the second subsection presents field tests at a small hydro station in Sweden.

Large-scale load modulation. Reference 7-7 describes how angle stability can be improved by large-scale active-load modulation. Analysis, operating experience, and simulation of a large power system is used to demonstrate that active-load modulation can improve system dynamic performance to a large extent, with just a fraction of the base load available for control. At a time when the cost effectiveness of power electronic devices for damping interarea oscillations is constantly being questioned, it's natural to look to active-load modulation as a potential alternative method of ensuring grid reliability. In developing the case, it was found that continuously modulating load stabilizers need global signals for full effectiveness. Although more difficult to design, implementation of discontinuous control schemes show good prospects, especially for decentralization and robustness against communication delays.

Damping of Power Oscillations by Load Switching—Field Tests at Hemsjö Hydro Power Station. Reference 7-8 presents field tests performed at the hydro power station Hemsjö Övre the night of 24 and 25 September 1996. The tests were done to investigate if load switching could be used to damp power oscillations. The results show that load switching is an excellent method of damping power oscillations.

The idea is to switch a resistive load so it counteracts power oscillations. The angle difference between the external net and the estimated generator internal EMK was used to control the load switching. The load used was pure resistance without any dynamics and was dedicated for this purpose.

To make the generator susceptible to power oscillations, the grid configuration was changed so the hydro power station had to feed its power through a weak distribution system before connecting to the main grid

A way to verify the damping effect of load switching is to change the sign in the controller, corresponding to a 180 degrees phase change. A change of sign in a well-tuned regulator can induce power oscillations. During the first 10 seconds in Figure 7-6 and 7-7 the regulator sign was changed. The figure clearly shows that the load switching builds up a power oscillation with increasing amplitude. Two measurements were done to compare damping. The first case is without load switching and in the second case is with load switching. Figure 7-6 with time > 10 second shows the damping without load switching.

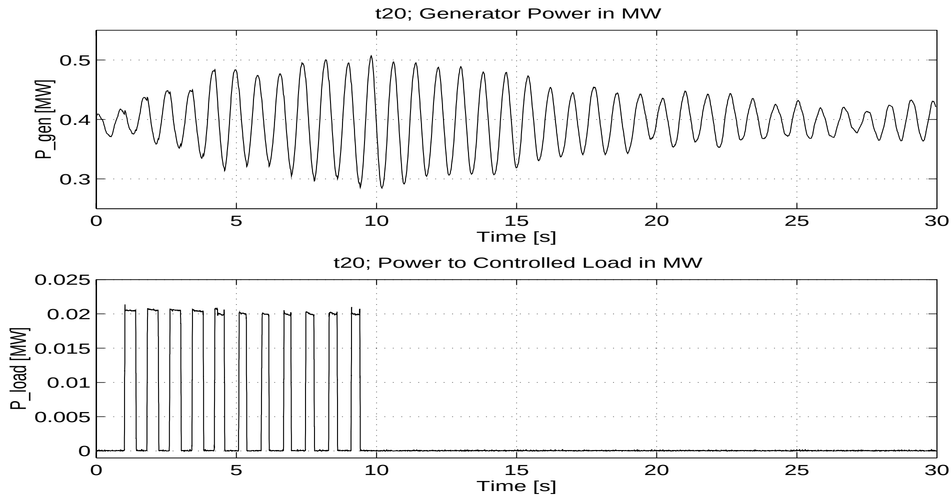

Fig. 7-6. Excitation with load switching (1-9s) and thereafter no switching.

Figure 7-7 shows the damping when load switching is used. It is evident that controlled load switching improves damping considerably. Note that the power of the switched load is only a fraction of the oscillation amplitude.

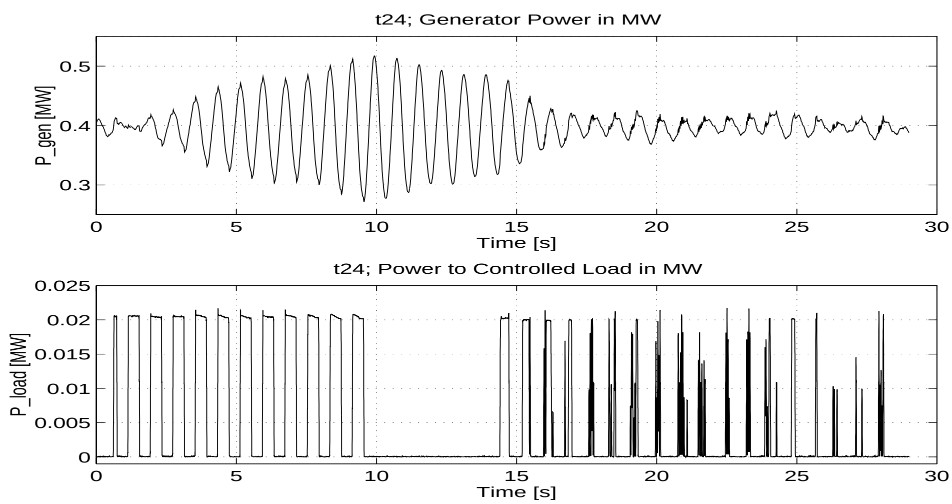

Fig. 7-7. Excitation by load switching (1–9 s), thereafter no switching (9–14 s), then damping by controlled load switching (14–30 s).

7.5 Active Power Modulation of Generators and Energy Storage for Oscillatory Instability Control

Energy Source Power System Stabilizer (ESPSS). The objective of the ESPSS is to damp low frequency electromechanical oscillations between large interconnected power systems. Field tests and monitoring have demonstrated the ESPSS performance in sensing system disturbances, and in controlling the power of batteries [7-9] and steam-turbine generators in response to these system oscillations.

The ESPSS can be applied on energy storage systems such as superconducting magnetic energy storage (SMES) or battery energy storage systems. The power import capability and the reliability can be increased significantly by damping the interarea power system oscillations that often limit such imports.

In the case of a battery energy storage system (BESS), ESPSS processes the frequency deviation signal or similar signal to control the megawatt output or input of the batteries. The ESPSS, which controls the real power output to counteract these oscillations, can provide effective damping. The ESPSS can be applied on the battery or superconducting energy storage by controlling the power conditioning system (PCS) which converts power between AC and DC. The state-of-the-art PCS using Gate-Turn-Off (GTO) thyristors are very fast acting and have the capability to accept both MVAr and the MW power orders. The ESPSS controls the MW output only.

Tests conducted at the 10 MW Chino battery energy storage system [7-10] demonstrated damping capability with measurable results. However, a much larger BESS or SMES is required to effectively damp and stabilize the system. Since the aim is to provide damping torques to generators, the most effective location of energy storage is close to generators participating in low frequency oscillations.

ESPSS installation on electric power generators. In damping interarea modes conventional PSS essentially modulates voltage-sensitive load, and the effectiveness depends on the location and characteristics of load, on the tightness of voltage control, and on the mode shape [7-11]. These factors affect the component of electrical torque in phase with (modal) speed that produces damping.

For generators, the ESPSS differs from conventional excitation equipment PSS in that it acts on the mechanical input power of the generator. It can be effective and robust in damping low frequency modes present in the speed signal, with less dependence on variable network and load characteristics, and generator loading.

The ESPSS concept is to produce damping more directly by modulating the mechanical input power instead of generator voltage and reactive power. This is by adding a speed or frequency deviation based signal into the governor valve controls. Similar to PSS, the input signal can be derived from speed/frequency and electrical power measurements. Appendix J further describes mechanical versus electrical side damping.

Field tests conducted on a turbo-generator with a state-of-the-art governor showed that steam-turbine governors can respond fast enough to provide damping of low frequencies oscillations (0.2–0.8 Hz range). Thus the ESPSS concept can be extended to the other steam-turbine governors. With a large power source it would be possible to damp the oscillations with even a small change (5 percent) of the generator output.

At Alamitos Generating Station in California, generators 5 and 6 steam turbines are cross-compound units and the steam flow is controlled on the high-pressure side. The steam control is obtained from eight valves. The opening and closing of the valves are controlled to obtain maximum operating efficiency and control. Tests were conducted by injecting the modulating signal in one and two different valves of these eight valves. Modulating two valves gave almost twice the modulated power output change compared to one valve. By modulating two valves, modulation of 5 percent of the turbine power (about 24 MW) can be achieved. The modulation input to the valve is dependent on the frequency excursion from 60 Hz and can be adjusted by changing the gain of the ESPSS.

Figure 7-8 shows the gain and the phase relationship of the governor loop measured by changing the input into the governor control board and monitoring the megawatt change in the machine output. The phase lag increases as the frequency of the modulation signal increases. At 1 Hz, the phase shift between the injected input signal and the power output increases to about 100 degrees. This phase shift includes delays in the steam circuit such as the steam chest. For damping control design, the transfer function between the valve input and mechanical power is required, and this can be computed from measurements of electrical power and speed. The modulation control includes phase compensation of the steam circuit lag so that the change in mechanical power is closely in phase with generator speed changes for oscillation frequencies of interest.

Figure 7-9 shows the response curve for the excitation system of a similar machine. The phase shift in this case is increases much more rapidly, increasing to about 180 degrees at about 0.7 Hz. However, the gain also drops rapidly making this control loop ineffective at these higher frequencies.

Although efforts to implement these controls were made in the past, it had not been feasible because the governors were generally slow. Also, the frequencies that were attempted were mostly local mode oscillations and were in the range of 1.0–3.0 Hz. The advanced state-of-the-art governors and the lower interarea oscillation frequencies have made this modulation feasible.

Two ESPSS have been developed and installed at Alamitos generating units 5 and 6. The ESPSS acts only for large system disturbances. It cuts off the excitation system PSS system when it operates as shown in Figure 7-10.

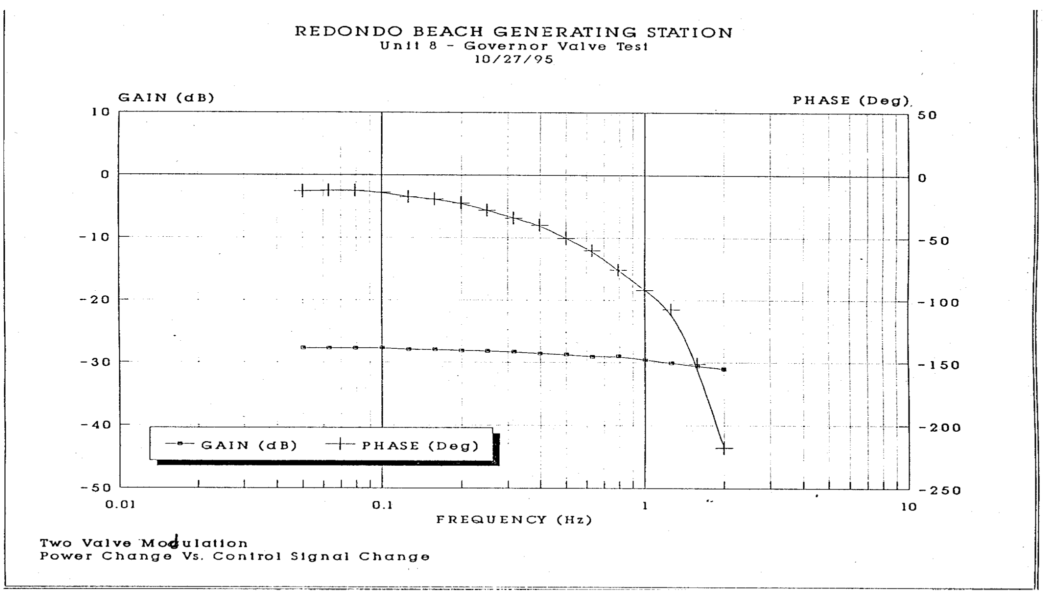

Fig. 7-8. Governor frequency response with signal input into two valves.

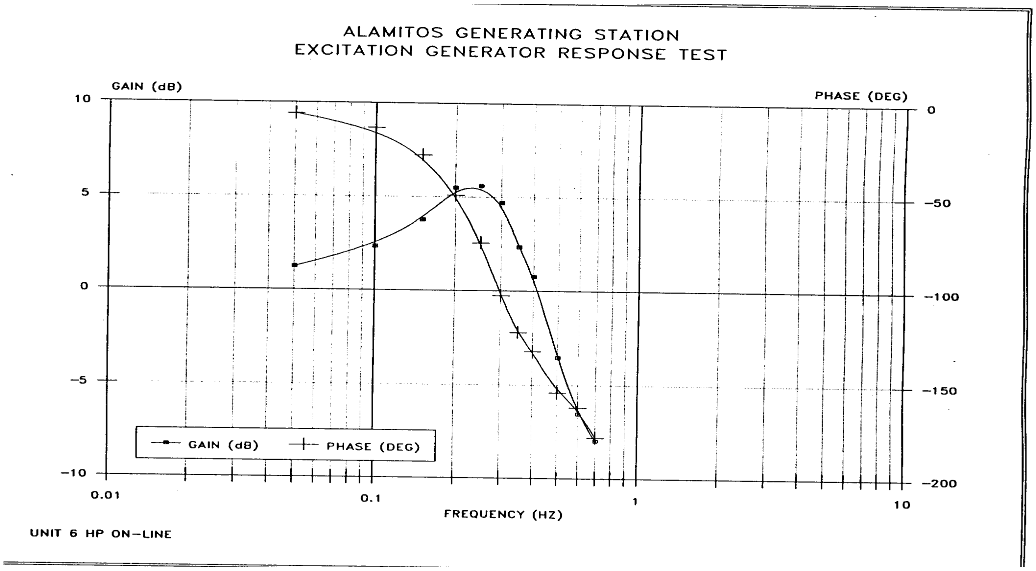

Fig. 7-9. Excitation system frequency response for Alamitos generating unit.

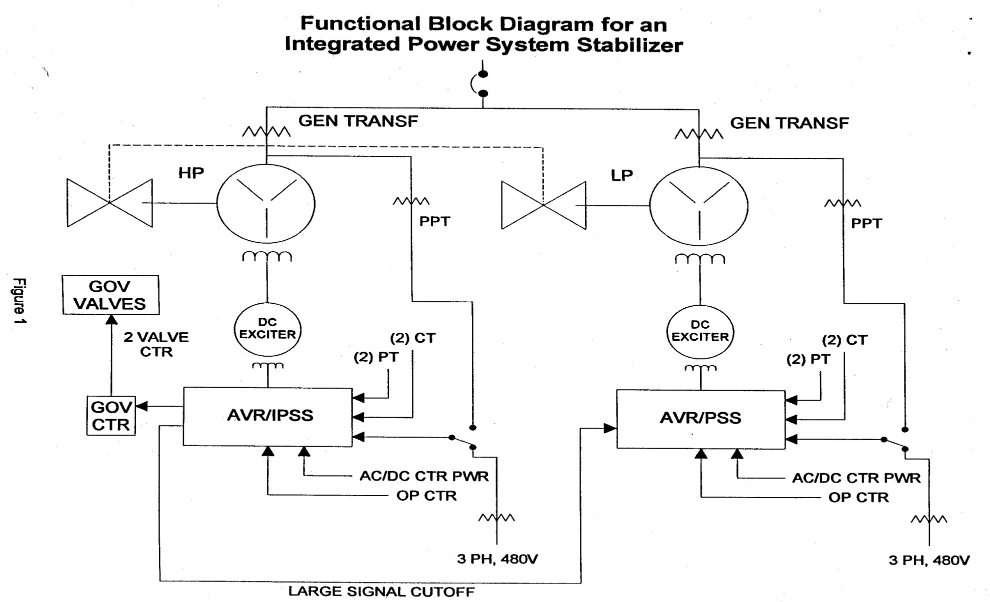

Fig. 7-10. Functional block diagram for an integrated power system stabilizer.

Rapid modulation of fuel flow in combustion turbines. In so-called "industrial" combustion turbines, the turbine compressor and power turbine are mechanically coupled to the synchronous generator and thus turn at a speed that is constantly proportional to synchronous speed. This arrangement, also called "single-shaft" combustion turbines, maintains constant air flow through the entire unit. With this constant air flow rate, the turbine power changes within milliseconds of changes in fuel flow into the combustors allowing the rapid power generation change that may be used to improve transient and oscillatory instability. For instance, it's possible for such a unit to shift from synchronous operation at minimum generation, approximately 30 % of nameplate power, to full nameplate power in less than a second by rapidly increasing fuel flow. The drawback to this process change lies in the fact that the power turbine temperatures also change rapidly with changes in firing rate, and the erosion rate of power turbine blades is seriously increased with large, rapid changes in firing rate and temperature. Utilities have experimented with these concepts and with rapidly increasing firing rate during emergencies such as loss of large blocks of generation, but we know of no in-service applications.

Similar to the above descriptions of small (5%) modulation of steam turbines, modulation of gas turbines should be possible without damaging temperature excursions. For two-sided modulation (increase and decrease of power), the gas turbine generator would have to be operated at lower efficiency, below maximum power. This might require an ancillary service arrangement, with compensation for the lost power sales and lower efficiency. The ancillary services could include system stability (damping), primary and secondary spinning reserve, and increased reactive power production or reactive power reserve.

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